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AIRBORNE LASER SYSTEMS*

by

James L. Harris

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1.0 INTRODUCTION

This report summarizes a brief study of the application of airborne pulsed laser systems to the detection of submerged submarines. The laser differs from conventional sources by virtue of extremely high peak powers coupled with short pulse lengths, and inherent narrow spectral bandwidth which makes possible highly selective filtering, thus allowing the rejection of a large portion of the "broadband" ambient lighting.

In a brief study such as the one which has been performed, it is not possible to treat in detail the many factors which determine the performance of this type of system. The numerical examples contained in this report will demonstrate that the rapid attenuation which the light pulse suffers in passing through the ocean water dominates the calculation. The exponential attenuation in the water is such that a given percentage change in any one factor translates into a much reduced percentage change in depth of detection.

The purpose of this study was to generate order-of-magnitude estimates of the potential capability of a pulsed laser ASW system. To this end a performance equation has been derived. This equation is then subjected to numerical evaluation for a number of sets of specific conditions chosen to show the relative

effects of variation of important factors. In addition to capability for submarine detection, a practical system must have a significant area search rate. This point is discussed in a latter section of this report. A final section offers a discussion of the results and recommendations as to future action.

2.0 DERIVATION OF EQUATIONS

2.1 Signal

Assume that a laser is mounted on an airborne platform directing a pulse vertically downward as shown in Fig. 1. The laser transmits a peak radiant power of P_T. If the beam transmittance of the atmosphere is denoted by T_A then the power reaching the water surface is

$$P_S = P_T T_A \quad . \tag{1}$$

At the air-water interface a fraction of the flux is reflected. The reflectance coefficient is a function of the two indices of refraction and the angle of incidence. The reflectance coefficient is relatively constant over a range of angles from perpendicular to roughly plus or minus 45 degrees. For an 18 knot wind the rms sea slope might be on the order of 15 degrees. Therefore for the case of moderate sea state and a pulse fired vertically downward, the reflectance can be considered to be a constant and will be designated as R_W. The flux passing through the air-water interface is therefore

$$P_W = P_T T_A (1-R_W) \quad . \tag{2}$$

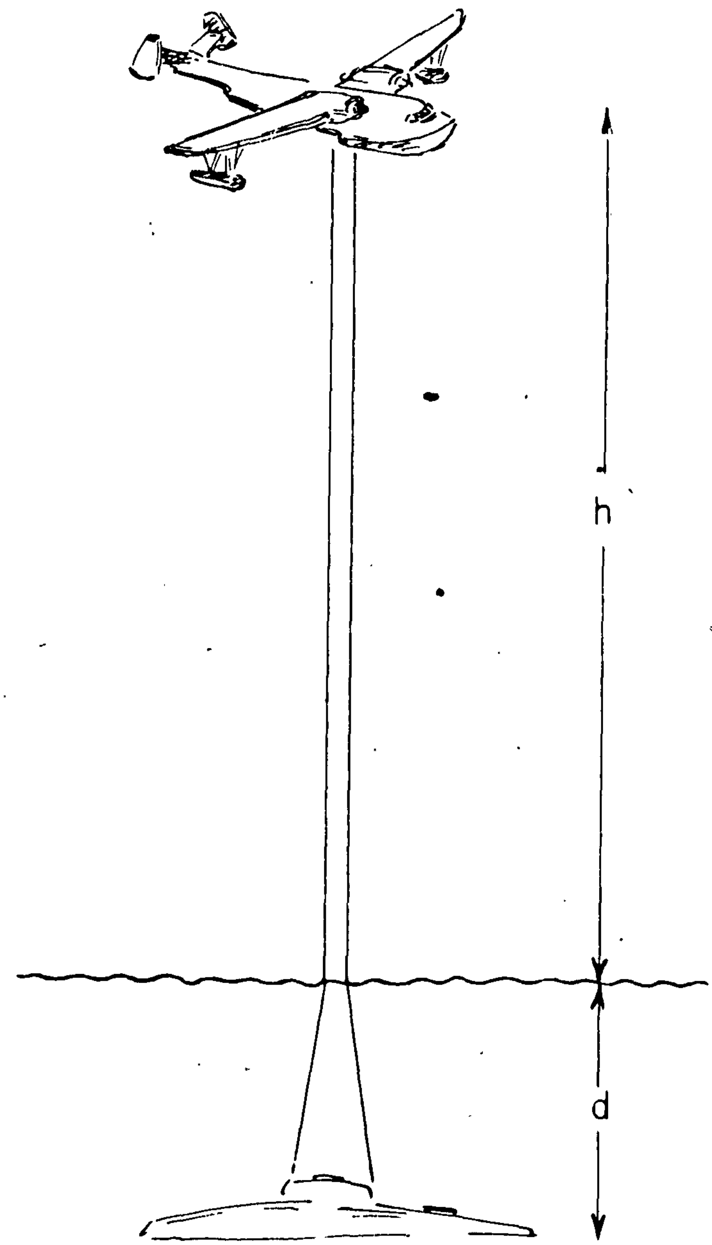

FIGURE 1 - THE GEOMETRY OF THE DOWNWARD PULSE TRANSMISSION

As the pulse penetrates the water to a depth d, it will be attenuated in an approximately exponential manner. Denoting the attenuation coefficient as α, the power at depth d is

$$P(d) = P_T T_A (1-R_W) \epsilon^{-\alpha d} \tag{3}$$

Equation (3) indicates the total flux or power at depth d but does not indicate its spatial distribution. The irregularities of the air-water interface coupled with the change in index of refraction serve to spread the beam. For example, a 15 degree water slope will, by Snell's law, induce a ray deviation on the order of 3.5 degrees. At a depth of 300 feet such a ray deviation would result in a beam spread of approximately ± 18 feet. At this depth and for a submarine of 30 foot beam, only a fraction of the pulse would strike the submarine. A thorough systems analysis would include a detailed study of pulse spread and its effect on detection statistics. As was indicated at an earlier point in this report the detection depth is relatively insensitive to moderate changes in linear factors such as this. For the purpose of this brief study it will be assumed that the spatial density of pulses is sufficiently high and the depth sufficiently small such that the probability is high that at least one pulse is a direct hit on the submarine. It should be recalled that for flat calm conditions this effect will be absent and that for wind velocities in excess of 18 knots the effect will be exaggerated.

If the submerged reflectance of the submarine is denoted by R_T, assumed to be Lambert, then the power reflected per unit

solid angle is

$$J = P_T T_A (1-R_W)\, \epsilon^{-\alpha d}\, \frac{R_T}{\pi}\ . \tag{4}$$

In traversing the path from the submarine back to the water surface there will once again be an attenuation $\epsilon^{-\alpha d}$. For the case of a flat calm sea the passage through the air-water interface will result in a ray deviation such as to make the airborne system appear to be at an altitude of 4/3 h where h is the actual altitude and the 4/3 term is the ratio of refractive indices. The flux received by the airborne optical system is found by multiplying Eq. (4) by the solid angle subtended by the receiving optical system with proper accounting for the attenuation of water, interface, and air paths. Thus

$$P_R = P_T T_A{}^2\, (1-R_W)^2\, \epsilon^{-2\alpha d}\, \frac{R_T}{\pi}\, \frac{A_L}{(d+4/3\ h)^2} \tag{5}$$

where A_L is the area of the receiver optical system.

Consider now the case of a water surface which is not flat but rather has some distribution of slopes. This aspect of the problem is perhaps most easily visualized by considering the case of a submerged point source as shown in Fig. 2.

First consider the case of a point source having a beam as shown by the solid lines in the top drawing. The effect of the sea slope distribution will be to broaden the beam so that only a fraction of the flux is received as is indicated by the solid lines of the lower drawing. The target in the application under

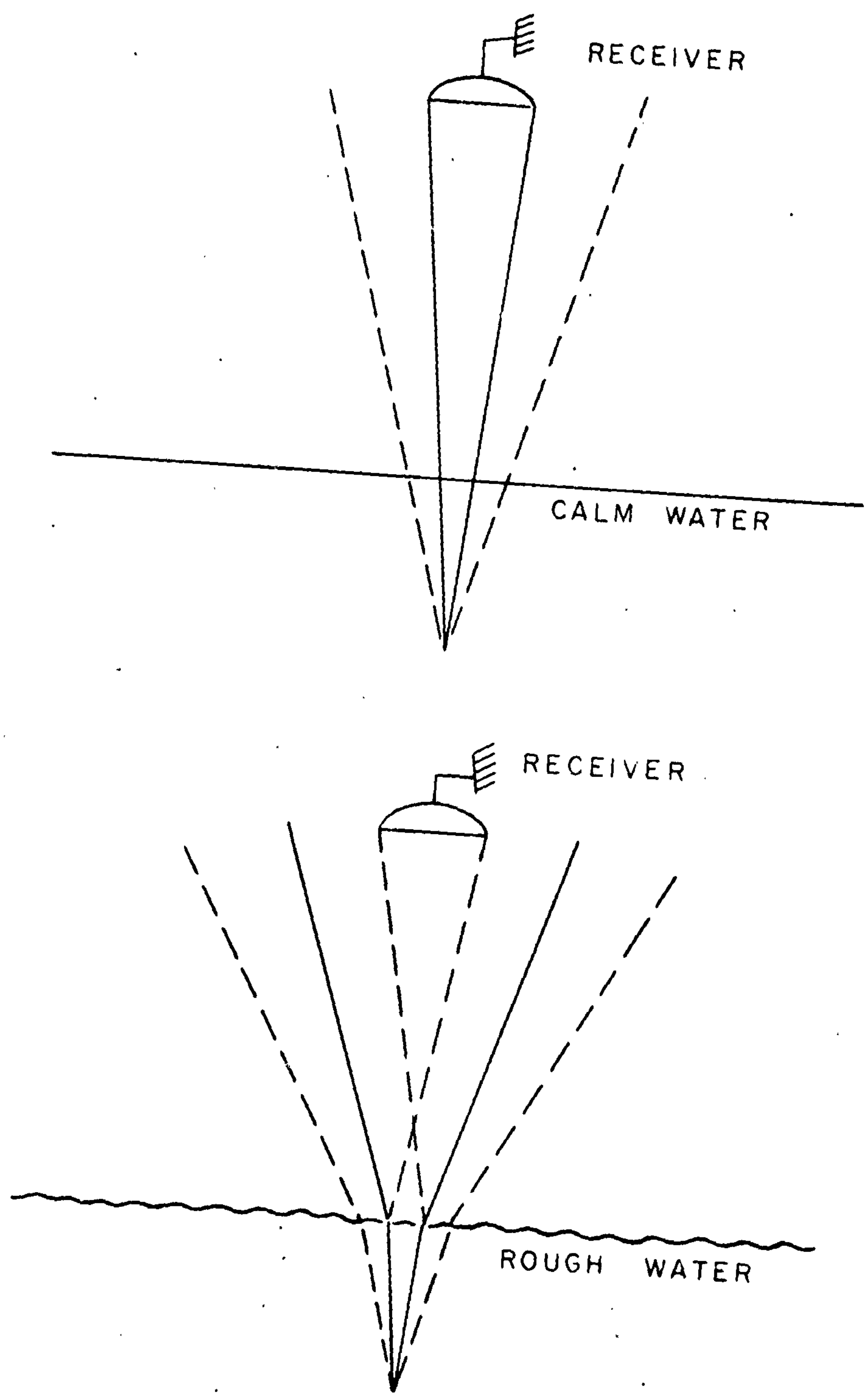

FIGURE 2 - EFFECT OF INTERFACE DISPERSION ON FLUX AT THE RECEIVER

consideration in this report is assumed to be a Lambert surface so that it radiates in all directions. The point source of Fig. 2 can be imagined to radiate in all directions by adding adjacent beams, shown dotted. As the sea surface is roughened each of these beams will be broadened by a similar amount. The central beam now contributes only a fraction of its flux to the receiver. The adjacent beams which initially made no flux contribution to the receiver now contribute a fraction of their total flux. The net result is that for moderate sea state conditions the returned flux from the pulse is independent of sea state.

It is important to note that as the sea surface is roughened the field of view of the receiver must be increased to take in that portion of the water's surface intercepted by those adjacent beams making flux contribution. Provided that this field of view requirement is met Eq. (5) is a good approximation for all air-water interface conditions up to moderate sea states.

The next step in deriving an expression for the signal return from the submarine is to convert Eq. (5) to photocell current by multiplying the return flux in watts by the photocell sensitivity in amperes per watt. Thus

$$i_R = P_T T_A{}^2 \, (1-R_W)^2 \, \epsilon^{-2ad} \, \frac{R_T}{\pi} \, \frac{A_L}{(d+4/3\ h)^2} \quad S. \tag{6}$$

In order to perform a detection it is necessary to distinguish the difference between the photocell current due to the presence of a submarine at depth d and the photocell current due to

backscatter from the water. It is therefore necessary to derive an expression for the photocell output due to backscatter from the water.

In Eq. (6) $\frac{R_T}{\pi}$ is the fraction of the incident flux which is returned from the target per unit solid angle. An equivalent concept exists in terms of scattering within the water. The term $\sigma(180^\circ)$ is the scattering function evaluated for the backscatter or 180° position. It is the fraction of incident flux returned per unit solid angle per meter of water. The scattering function is based on energy measurements. It is therefore directly related to the probability of scatter of a single photon. The signal return from a flat plate submersed in the water would be a pulse whose temporal signature is identical to the transmitted pulse. It is therefore necessary to determine how many photons on the average will be returned within the time interval, equal to a pulse length, which corresponds to the return from a flat plate at a depth, d.

A photon in the leading edge of the pulse would be returned within the indicated time interval if it was backscattered at a depth, d, in which case it would appear at the leading edge of the return pulse. It would also be within the indicated time interval if it was backscattered at any time up to and including that time which would correspond to the trailing edge of the return pulse. If the pulse is of temporal duration τ, then this corresponds to a range of depths

$$d < d' < d + \frac{c_W \tau}{2}. \tag{7}$$

The term C_W is the velocity of light in water. The factor of two in the denominator results from the fact that the round trip of the photon to the increased depth must be equal to $C_W\tau$.

A photon in the trailing edge of the pulse will be within the indicated time interval if it is scattered from a depth d, in which case it will appear at the trailing edge of the return pulse or at lesser depths up to and including that depth which will make the photon appear in the leading edge of the return pulse. This corresponds to a range of depths

$$d - \frac{C_W\tau}{2} < d' < d \ . \tag{8}$$

Thus each photon has a depth interval $\frac{C_W\tau}{2}$ within which the return may be confused with the return from a target at depth d. Therefore if $\sigma(180^o)$ is multiplied by $\frac{C_W\tau}{2}$ the resultant is an equivalent reflectance for the water. The photocell output from the backscattering in the water is therefore

$$i_W = P_T T_A{}^2 \ (1-R_W)^2 \ \epsilon^{-2\alpha d} \ \frac{\sigma(180^o)C_W\tau}{2} \ \frac{A_L}{(d+4/3\ h)^2} \ S \ . \tag{9}$$

In order to detect an object it is necessary to sense the difference between the condition of target-present and target-not-present. The signal current is therefore the difference between Eqs. (6) and (9) or

$$i_S = P_T T_A{}^2 \ (1-R_W)^2 \ \epsilon^{-2\alpha d} \ \frac{A_L S}{(d+4/3\ h)^2} \left[\frac{R_T}{\pi} - \frac{\sigma(180^o)C_W\tau}{2}\right] \ . \tag{10}$$

2.2 Noise

There are three primary noise sources which should be considered. They are photon shot noise due to the ambient lighting, photon shot noise due to the backscatter return from the water and shot noise due to the photocell dark current. The total rms noise is given by the expression

$$i_n = \sqrt{2\, e\Delta f(i_W+i_A+i_{DC})} \tag{11}$$

where e is the electronic charge, Δf is the system electrical bandwidth, and i_W, i_A, and i_{DC} are the photocell direct current components from water backscatter, ambient light, and dark current respectively. Equation (9) is the expression for i_W. The ambient flux current i_A is

$$i_A = N(\lambda)\Delta\lambda A_L \Omega S \tag{12}$$

where $N(\lambda)$ is the apparent radiance of the sea surface for a wavelength λ, $\Delta\lambda$ is the wavelength interval passed by the optical system, A_L and S are as previously defined, and Ω is the solid angle of the receiver field of view.

2.3 Signal-to-Noise Ratio

The signal-to-noise ratio is Eq. (10) divided by Eq. (11) or

$$\frac{S}{N} = \frac{P_T T_A^2 (1-R_W)^2 \epsilon^{-2\alpha d} \frac{A_L S}{(d+4/3\ h)^2} \left[R_{T/\pi} - \frac{\sigma(180^\circ) C_W \tau}{2} \right]}{\left[2e\Delta f \left\{ P_T T_A^2 (1-R_W)^2 \epsilon^{-2\alpha d} \frac{\sigma(180^\circ) C_W \tau}{2} \frac{A_L S}{(d+4/3\ h)^2} + N(\lambda)\Delta\lambda A_L \Omega S + i_{DC} \right\} \right]^{1/2}} . \quad (13)$$

This equation describes the capability for detection of the pulse reflected from the submarine. Detection performance will be near maximum where

$$f = \frac{1}{\tau} . \quad (14)$$

Therefore

$$\frac{S}{N} = \frac{P_T \tau^{1/2} T_A^{1/2} (1-R_W)^2 \epsilon^{-2\alpha d} \frac{A_L S}{(d+4/3\ h)^2} \left[\frac{R_T}{\pi} - \frac{\sigma(180^\circ) C_W \tau}{2} \right]}{\left[2e \left\{ P_T T_A^2 (1-R_W)^2 \epsilon^{-2\alpha d} \frac{\sigma(180^\circ) C_W \tau}{2} \frac{A_L S}{(d+4/3\ h)^2} + N(\lambda)\Delta\lambda A_L \Omega S + i_{DC} \right\} \right]^{1/2}} . \quad (15)$$

Examination of Eq. (15) indicates the following relationships. The signal-to-noise ratio is <u>increased</u> by <u>increasing</u> the transmitted power, the atmospheric transmittance, the area of the receiver optical system, the photocell sensitivity, and the reflectance of the submarine. The signal-to-noise ratio is <u>increased</u> by <u>decreasing</u> the attenuation of the water path, the depth of detection, the altitude of the airborne system, the backscattering coefficient, the apparent radiance of the sea surface,

the bandwidth of the optical filter, and the dark current.

The effect of varying pulse length is a little more complex and is dependent on which noise source is dominant. Where the noise is dominated by the component due to flux backscattered from the water the dependence on pulse length is confined to the "difference in reflectance" term in the bracket. It is interesting to note that the return in the presence of a target can be near zero with an inappropriate choice of pulse length and can be of either positive or negative sign for very short and very long pulse lengths respectively. Caution should be exercised in extending the equation to very long pulse lengths because the equivalent water reflectance is an approximate form for reflectance from a relatively thin lamina of water. Where the pulse length is large exponential decay and inverse square effects will prevent the equivalent reflectance from being linearly proportional to pulse length. The equivalent reflectance will in fact approach an asymptotic value for large pulse lengths.

For the case of noise dominated by either ambient light or photocell dark current, the effect of pulse length is dependent on the product of τ and the equivalent reflectance term. In any case it must be realized that increasing pulse length, while maintaining constant peak power, is linearly increasing the energy per pulse.

3.0 NUMERICAL EVALUATION

In this brief study it was not possible to subject all of the system variables to thorough investigation. The best that could be accomplished was to choose seven cases of interest, each of which represents a change of some important variable. This allows an

opportunity to display the sensitivity of detection depth to the selected variables and serves to give crude bracketing to system performance.

The calculation is of course completely dependent on the existence now or in the near future of laser sources having the desired characteristics. This laboratory does not have first hand information on the state-of-the-art of laser sources. The first calculational efforts of this laboratory were on behalf of the Air Force Aeronautical Systems Command, Wright-Patterson AFB, Ohio. The brief calculation performed for this group was guided by their informal statement to the effect that a laser having peak power of 10^7 watts, a 10 000 pulse per second repetition rate, and 0.01 microsecond pulse length was a reasonable calculational choice. This statement also served as a guide for the present calculation although peak powers an order of magnitude higher and lower are also plotted. Water being highly spectrally selective dictates that the laser should operate on or near 480 mμ which is the approximate wavelength of peak transmission of the water.

Additional discussion on the selection of variables is contained in the section, Conclusions and Recommendations. The numerical values of the system variables utilized in the calculations are summarized in Table I.

Figure 3 shows signal-to-noise ratio as a function of depth for various choice of variables. At the request of the Bureau of Weapons the calculation was extended to include the case of satellite altitudes. They requested that an altitude of 300 nautical miles be assumed, and that utilizing some sort of balloon-like structure a receiving aperture of 100 foot diameter be utilized. The increase in altitude results in a decrease in the solid angle of collection required by the receiver by an amount proportional to the square of the altitude ratio. All other

TABLE I

P_T	$= 10^6, 10^7, 10^8$ watts radiant power
τ	$= 10^{-8}$ seconds
T_A	= 0.5 (Visibility Laboratory flight data values of .067, .432, .586, .613, .914) for 5000 feet and 1.0 for 50 feet)
α	= 0.1/meter
R_W	= 0.02
S	= 0.03 amperes/watt
R_T	= 0.016 (Visibility Laboratory data values of 0.0152, 0.164 for spec. nos. 122-1 and 122-3)
$\sigma(180^\circ)$	$= 5.4 \times 10^{-4}$/ster-meter
C_W	$= 2.26 \times 10^8$ meters/second
e	$= 1.6 \times 10^{-19}$ coulombs
$N(\lambda)$	$= 3 \times 10^{-4}$ watts/ster - ft^2-A° (Visibility Laboratory data)
$\Delta\lambda$	= 5 A°
i_{DC}	$= 0.6 \times 10^{-14}$ amperes (Engstrom, J. Opt. Soc. Am., 37, No. 6, June 1947)
Ω	$= 8 \times 10^{-4}$ for 5000 ft rough sea
Ω	$= 2.64 \times 10^{-1}$ for 50 ft rough sea
Ω	$= 4.08 \times 10^{-6}$ for 5000 ft calm sea
Ω	$= 1.35 \times 10^{-3}$ for 50 ft calm sea
A_L	$= 9\pi$ square ft (6 foot diameter)
h	= 50, 5000 ft.

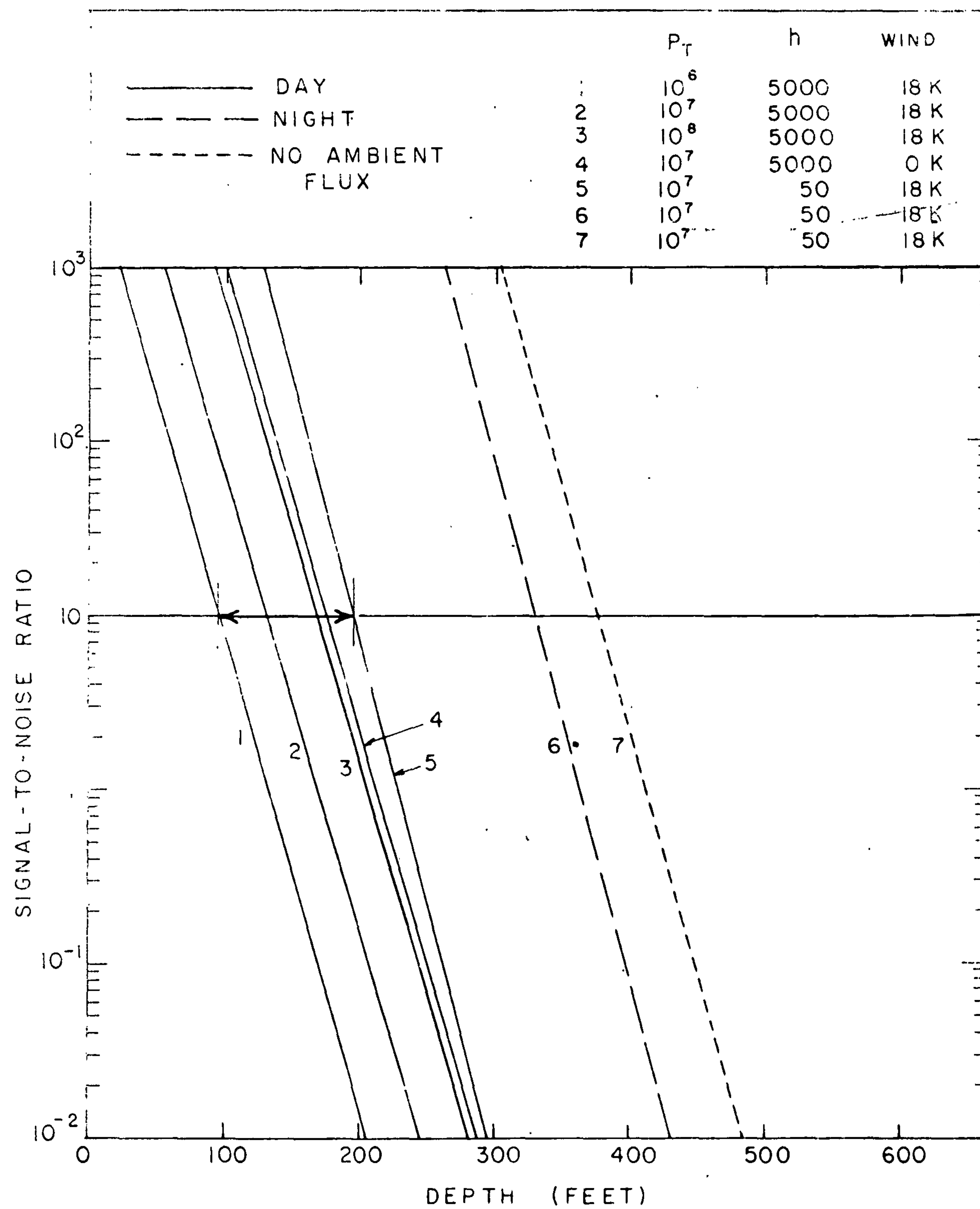

FIGURE 3 - PERFORMANCE PREDICTIONS

assumptions are identical with those listed in Table I. The results of this secondary calculation are shown in Fig. 4.

4.0 DISCUSSION OF RESULTS

The curves of Fig. 3 clearly show that the detection problem is dominated by the attenuation characteristics of the water. If it is assumed that a signal-to-noise ratio of 10 is required for practical operation then the detection depths can be compared for various choice of variables.

Curves 1 and 3 differ only in their value of peak transmitted power. They demonstrate that an increase in peak power by a factor of 100 to 1 changes the detection depth from roughly 95 to 170, a factor of less than 2 to 1.

Comparison of curves 2 and 5 shows the effect of altitude change. By decreasing the altitude from 5000 feet to 50 feet (100 to 1) the detection depth is increased from 130 feet to 195 feet (considerably less than 2 to 1).

Comparison of curves 2 and 4 shows the effect of sea state. The difference between flat clam sea and 18 knots wind is the difference between 130 feet and 175 feet detection depth.

Curves 5 and 6 are identical with the exception that 5 is for full daylight and 6 is for night. This illustrates the important point that for 5 A° spectral filtering as assumed in this study, the dominant noise is that due to the ambient light level. Curve 7 shows the situation if the ambient light level is removed. Curve 7 could become a reality for both day and night operation if coherent or

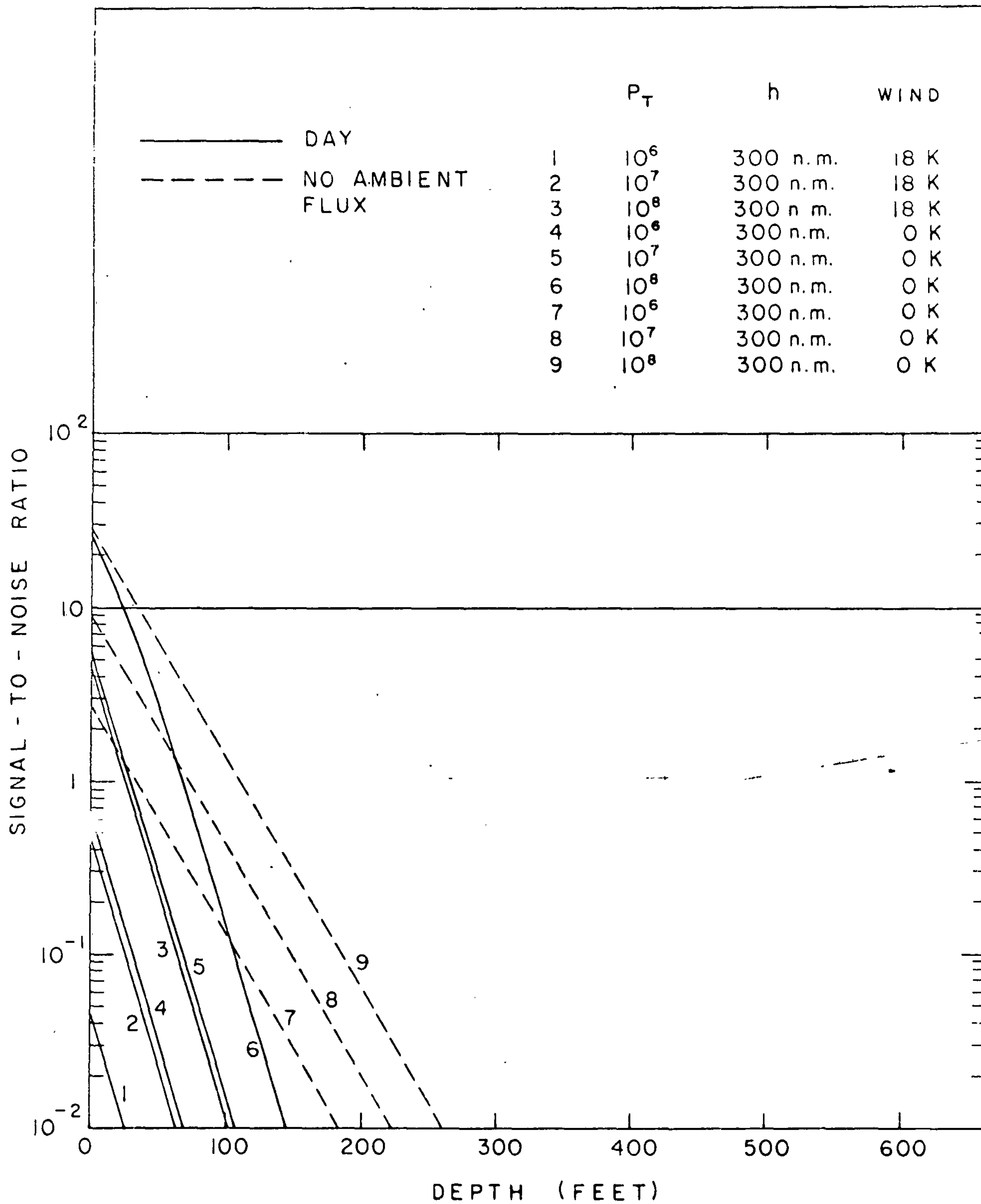

FIGURE 4 - PERFORMANCE PREDICTIONS

hetrodyning detection could be efficiently accomplished with the resulting extremely narrow spectral bandwidths.

Figure 4 is graphic illustration of the effect of the inverse square law relationship with altitude. The decrease in signal return due to the increase in altitude from 5000 feet to 300 nautical miles amounts to a factor on the order of 1.3×10^5. The receiver aperture area was increased by a factor of roughly 2.8×10^2 so that the net effect is still an overall reduction in signal strength by a factor of 4.6×10^2. It is therefore not surprising that the calculated detection depths are small.

The next section indicates the power requirements implied in the calculation. The implication of the high power requirement to a satellite system must be considered.

5.0 AREA SEARCH RATE CONSIDERATIONS

In order for the system to be considered feasible it must not only be capable of performing detections at a reasonable depth but must also be capable of covering the search area in a reasonable period of time. A detailed study of this aspect of the problem has not been made. This section reports a very simple calculation for the purpose of indicating the order of magnitude of area search capability of such a system.

At an earlier point in this report it was stated that the pulse density on the water surface would be made sufficiently high so that there was a good probability of at least one pulse making a direct hit on the submarine. This statement would probably be satisfied if the distance between adjacent pulses was on the order of 30 feet (the

target width). Because of the random azimuth orientation of the submarine and because of the large ratio of length-to-beam such an array should yield a high probability of direct hit.

Under these conditions the area associated with a single pulse would be 900 square feet. Section 3.0 indicated an assumed pulse repetition rate of 10^4 pulses per second. The resultant area searched per second would be

$$\mathring{A}_S = 9 \times 10^6 \text{ square feet/second} \quad (16)$$

or

$$\mathring{A}_S = 900 \text{ square nautical miles/hour.} \quad (17)$$

This rather large rate does not appear to be compatible with assumptions inherent in the detection calculation. For example even assuming a high speed aircraft, for example 600 knots, a sweep width of approximately 1.5 miles would be required in order to match the area search rate of 900 square nautical miles per hour. For the 5000 foot altitude case this would imply angles of incidence of the light pulse with the water on the order of 45 degrees. In addition to the interface problems the long slant paths through the water would severely limit detection depth. It is quite clear that for the 50 foot altitude case, a 900 square nautical mile per hour search rate is meaningless.

Area search rate considerations therefore indicate the

desirability of increased altitude whereas considerations of detection depth indicate the desirability of decreased altitude. A more thorough study would determine the best compromise.

The system power requirements are also directly related to area search rate. For a laser system having 10^7 watts peak power and a pulse length of 10^{-8} seconds, the energy per pulse is 10^{-1} watt-seconds or joules. With a pulse repetition rate of 10^4 pulses per second the average radiant power is 1000 watts. If the conversion from electrical input power to radiant power has an efficiency of K percent then the input power is 1/K kilowatts. If the pulse repetition rate was dropped to 10^3 pulses per second the area search rate would become 90 square nautical miles per hour and the input power 100/K watts. These efficiency figures must be obtained in order to determine what limitations may be imposed by the power generation capability of the airborne vehicle.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This brief study has served to indicate that an airborne laser system might accomplish submarine detection at depths up to several hundred feet during daytime operations and upwards of 300 feet during night-time operations. It has also indicated that area search rates on the order of several hundred square nautical miles per hour are potentially possible. If these system performance estimates compare favorably with alternate systems for accomplishing submarine detection then further study of such a system is required.

A more detailed study should include the following items:

1. Investigation should be made as to the present and projected state-of-the-art in laser systems. Specifically it is necessary to

determine the present and future capabilities with respect to

a. Peak power

b. Pulse duration

c. Radiation wavelength (assessed from the point of view of water transmission characteristics)

d. Pulse repetition rate

e. Conversion efficiency (electrical power to radiant power)

2. Investigation should be made as to the present and projected state-of-the-art on narrow spectral filtering.

3. A more thorough analysis should be performed with the goal of making more accurate predictions of system capability. Particular emphasis should be placed on the transmission and scattering properties of the water and air-water interface. These studies should be augmented by experimental measurements where necessary.

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